MODELING THE EARTH'S IONOSPHERE

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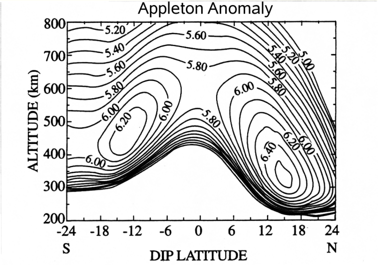
OVERVIEW

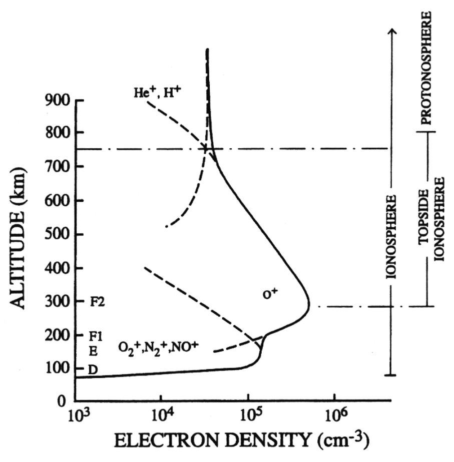
- What is the ionosphere?
- What are the ingredients of a model, i.e., the physics?
- How is it a model built, i.e., the numerics?
- What are some results?

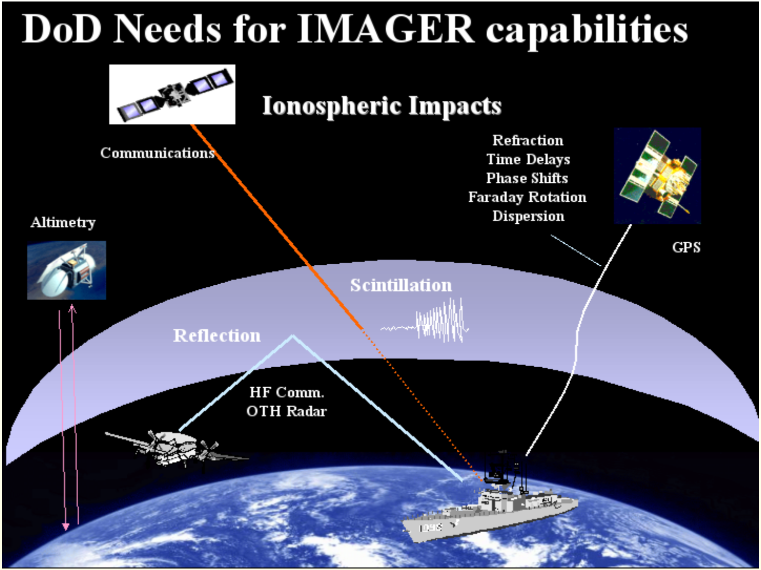
WHAT IS THE IONOSPHERE?

- Shell of partially ionized gas surrounding the earth
- Altitude: 80 km – few 1000 km
- Ionic species:

  Atomic: H^+, He^+, N^+, O^+
  Molecular: N_2^+, NO^+, O_2^+






DoD Needs for IMAGER capabilities
Ionospheric Impacts
Communications
Refraction
Time Delays
Phase Shifts
Faraday Rotation
Dispersion
GPS
Altimetry
Scintillation
Reflection
HF Comm.
OTH Radar

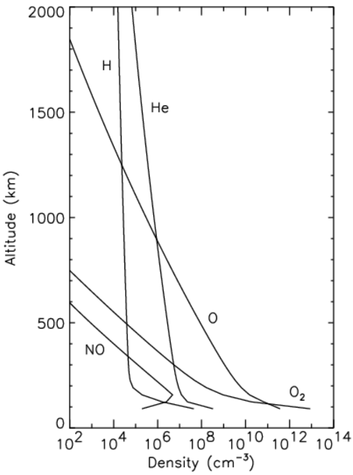
WHAT ARE THE INGREDIENTS?

- Neutral atmosphere
- Photoionization
- Chemistry
- Magnetic field
- Electric field
- Plasma dynamics

NEUTRAL ATMOSPHERE

- Dominant species:
  Atomic: H, He, N, O
  Molecular: N_2, NO, O_2
- Neutral density scale height:

$$H = kT/mg$$



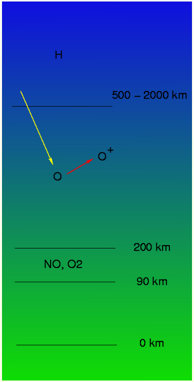
NEUTRAL ATMOSPHERE MODELS

- Empirical models
  - NLRMSISE-00 (*Picone et al.*)
    Provides neutral densities and temperature
  - HWM (*Hedin*)
    Provides neutral wind
- First principle models
  - NCAR TIME-GCM (*Roble*)
  - CTIP (*Fuller-Rowell*)

PHOTOIONIZATION

- Dominant production mechanism for ionospheric plasma
- Solar X-ray (1 – 170 Å) and EUV (170 – 1750 Å) radiation can ionize the ionosphere neutral gas

Species	IP (ev)	λ (Å)
H	13.6	912
He	24.6	504
N	14.5	853
O	13.6	911
N_2	15.6	796
NO	9.3	1340
O_2	10.1	1027

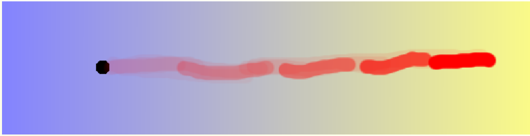


PHOTOIONIZATION: CALCULATION

- Production (P) needs to be calculated
- Continuity equation for ion species X

$$dX/dt = P_X = n_n(X) I_R \quad \text{where}$$

$$P_X = n_n(X) \sum_{\lambda} \underbrace{\sigma_X^{(i)}(\lambda)}_{\text{photoionization}} \underbrace{\exp\left[-\sum_m \sigma_m^{(a)}(\lambda) \int_z^{\infty} n_m(s)\, ds\right]}_{\text{photoabsorption}} \underbrace{\phi_{\infty}(\lambda)}_{\text{solar flux}}$$



PHOTOIONIZATION: SOLAR FLUX MODELS

- Empirical models: flux $\phi_\infty(\lambda)$ is in 37 wavelength bins
  - Hinteregger
  - Torr and Torr
  - EUVAC (*Richards et al.*, 1994)
    Function of geophysical conditions
    $\phi_i = F74113_i[1 + A_i(P - 80)]$ where
    $P = (F10.7A + F10.7)/2$
- Data/model driven
  - NRLEUV (*Lean, Warren, and Mariska*)
  - SOLAR2000 (*Tobiska*)
- Photoionization/photoabsorption cross-sections tabulated

- Production (P) and loss (L) mechanism
- Continuity equations for ion species X^+ and Y^+

$$dX^+/dt = P_{X+} - L_{X+} \quad \text{(e.g., } dH^+/dt = P_{H+} - L_{H+}\text{)}$$
$$dY^+/dt = P_{Y+} - L_{Y+} \quad \text{(e.g., } dO^+/dt = P_{O+} - L_{O+}\text{)}$$

- General chemical reaction (e.g., charge exchange)

$$X^+ + Y \rightarrow X + Y^+ \quad \mathrm{Rate}: k_{X+Y}$$
$$\text{(e.g., } H^+ + O \rightarrow H + O^+ \quad \mathrm{Rate}: k_{H+O}\text{)}$$

- Thus, in continuity use

$$L_{X+} = P_{Y+} = k_{X+Y}\, n(X^+) n(Y)$$
$$\text{(e.g., } L_{H+} = P_{O+} = k_{H+O}\, n(H^+) n(O)\text{)}$$

CHEMICAL REACTION RATES

Chemical Reaction Rates:

Reaction	Rate, $cm^3 s^{-1}$
$H^+ + O \rightarrow O^+ + H$	$2.2 \times 10^{-11} T^{0.5}(\mathrm{H}^+)$
$He^+ + N_2 \rightarrow N_2{}^+ + He$	3.5×10^{-10}
$He^+ + N_2 \rightarrow N^+ + N + He$	8.5×10^{-10}
$He^+ + O_2 \rightarrow O^+ + O + He$	8.0×10^{-10}
$He^+ + O_2 \rightarrow O_2{}^+ + He$	2.0×10^{-10}
$N^+ + O_2 \rightarrow NO^+ + O$	2.0×10^{-10}
$N^+ + O_2 \rightarrow O_2{}^+ + N(2D)$	4.0×10^{-10}
$N^+ + O \rightarrow O^+ + N$	1.0×10^{-12}
$N^+ + NO \rightarrow NO^+ + O$	2.0×10^{-11}
$O^+ + H \rightarrow H^+ + O$	$2.5 \times 10^{-11} T_n^{0.5}$
$O^+ + N_2 \rightarrow NO^+ + N$	k_1
$O^+ + O_2 \rightarrow O_2{}^+ + O$	k_2
$O^+ + NO \rightarrow NO^+ + O$	1.0×10^{-12}
$N_2{}^+ + O \rightarrow NO^+ + N(2D)$	$1.4 \times 10^{-10} T_{300}^{-0.44}(\mathrm{O}+)$
$N_2{}^+ + O_2 \rightarrow O_2{}^+ + N_2$	$5.0 \times 10^{-11} T_{300}^{-0.5}(\mathrm{O}+)$
$N_2{}^+ + O_2 \rightarrow NO^+ + NO$	1.0×10^{-14}
$N_2{}^+ + NO \rightarrow NO^+ + N_2$	3.3×10^{-10}
$O_2{}^+ + N \rightarrow NO^+ + O$	1.2×10^{-10}
$O_2{}^+ + N(2D) \rightarrow N^+ + O_2$	2.5×10^{-10}
$O_2{}^+ + NO \rightarrow NO^+ + O_2$	4.4×10^{-10}
$O_2{}^+ + N_2 \rightarrow NO^+ + NO$	5.0×10^{-16}

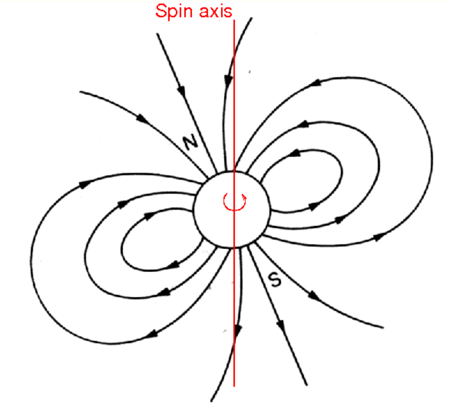
Recombination Rates:

Reaction	Rate, $cm^3\ s^{-1}$
$H^+ + e \rightarrow H$	$4.43 \times 10^{-12}/T_e^{0.7}$
$He^+ + e \rightarrow He$	$4.43 \times 10^{-12}/T_e^{0.7}$
$N^+ + e \rightarrow N$	$4.43 \times 10^{-12}/T_e^{0.7}$
$O^+ + e \rightarrow O$	$4.43 \times 10^{-12}/T_e^{0.7}$
$N_2{}^+ + e \rightarrow N_2$	$1.80 \times 10^{-7}/T_e^{0.39}$
$NO^+ + e \rightarrow NO$	$4.20 \times 10^{-7}/T_e^{0.85}$
$O_2{}^+ + e \rightarrow O_2$	$1.60 \times 10^{-7}/T_e^{0.55}$

$$\begin{aligned}
k_1 &= 1.53 \times 10^{-12} - 5.92 \times 10^{-13} T_{300}(\mathrm{O}^+) \\
&\quad +8.60 \times 10^{-14} T_{300}^2(\mathrm{O}^+) \text{ for } T(\mathrm{O}^+) < 1700K \\
k_1 &= 1.73 \times 10^{-12} - 1.16 \times 10^{-12} T_{300}(\mathrm{O}^+) \\
&\quad +1.48 \times 10^{-13} T_{300}^2(\mathrm{O}^+) \text{ for } T(\mathrm{O}^+) > 1700K \\
k_2 &= 2.82 \times 10^{-11} - 7.74 \times 10^{-12} T_{300}(\mathrm{O}^+) \\
&\quad +1.07 \times 10^{-12} T_{300}^2(\mathrm{O}^+) - 5.17 \times 10^{-14} T_{300}^3(\mathrm{O}^+) \\
&\quad +9.65 \times 10^{-16} T_{300}^4(\mathrm{O}^+) \\
T_{300} &= T/300
\end{aligned}$$

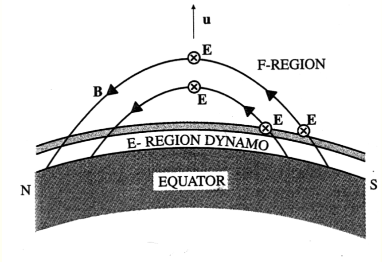
MAGNETIC FIELD

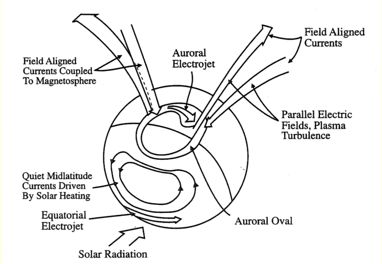
- Appropriate field: IGRF
- Modeled as a tilted (offset) dipole field, or IGRF-like
- Low- to mid-latitude:
  closed field lines
- High latitude:
  open field lines
- Important assumption:
  field lines are equipotentials



ELECTRIC FIELD

- Low latiutde: driven by neutral wind
  - Empirical models (e.g., Fejer-Scherliess)
  - Self-consistently determined (e.g., Eccles, Richmond)
- High latitude: driven by solar wind/magnetosphere currents
  - Empirical models (e.g., Heppner-Maynard)
  - Self-consistently determined from global magnetospheric models (e.g., LFM, RCM)





- Ion Continuity

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_i) = P_i - L_i n_i$$

- Ion Velocity

$$\left(0 \text{ or } \frac{\partial \mathbf{V}_i}{\partial t} + \mathbf{V}_i \cdot \nabla \mathbf{V}_i\right) = -\frac{1}{\rho_i} \nabla \mathbf{P}_i + \frac{e}{m_i} \mathbf{E} + \frac{e}{m_i c} \mathbf{V}_i \times \mathbf{B} + \mathbf{g}$$

$$-\nu_{in} (\mathbf{V}_i - \mathbf{V_n} - \sum_j \nu_{ij} \left(\mathbf{V}_i - \mathbf{V}_j\right)$$

- Ion Temperature

$$\frac{\partial T_i}{\partial t} + \mathbf{V}_i \cdot \nabla T_i + \frac{2}{3} T_i \nabla \cdot \mathbf{V}_i + \frac{2}{3} \frac{1}{n_i k} \nabla \cdot \mathbf{Q}_i = Q_{in} + Q_{ij} + Q_{ie}$$

- Electron Momentum

$$0 = -\frac{1}{n_e m_e} b_s \frac{\partial P_e}{\partial s} - \frac{e}{m_e} E_s$$

- Electron Temperature

$$\frac{\partial T_e}{\partial t} - \frac{2}{3} \frac{1}{n_e k} b_s^2 \frac{\partial}{\partial s} \kappa_e \frac{\partial T_e}{\partial s} = Q_{en} + Q_{ei} + Q_{phe}$$

HOW IS THE MODEL BUILT?

- Transport
  - Parallel
  - Perpendicular
- Grid
  - Lagrangian
  - Eulerian

- Continuity equation

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_i) = P_i - L_i n_i$$

$$\frac{\partial n_i}{\partial t} + \nabla_{\parallel} \cdot (n_i \mathbf{V}_{i\parallel}) + \nabla \cdot (n_i \mathbf{V}_{i\perp}) = P_i - L_i n_i$$

  - Parallel motion (diffusion/advection)

$$\frac{\partial n_i}{\partial t} + \nabla_{\parallel} \cdot (n_i \mathbf{V}_{\parallel i}) = P_i - L_i n_i \quad \text{for} \quad t \xrightarrow{\Delta t} t*$$

  - Perpendicular motion (advection)

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_{\perp i}) = 0 \quad \text{for} \quad t* \xrightarrow{\Delta t} t + \Delta t$$

PARALLEL TRANSPORT

Conventional Method: Ignore Ion Inertia

$$\frac{\partial n_i}{\partial t} + b_s^2 \frac{\partial}{\partial s} \frac{n_i V_{is}}{b_s} = P_i - L_i n_i$$

$$0 = -\frac{1}{n_i m_i} b_s \frac{\partial (P_i + P_e)}{\partial s} + g_s - \nu_{in}(V_{is} - V_{ns}) - \sum_j \nu_{ij}(V_{is} - V_{js})$$

- Procedure:
  - $\longrightarrow$ solve for ion velocity V_{is}
  - $\longrightarrow$ substitute into continuity
  - $\longrightarrow$ expand density $n_i \simeq n_{i0} + n_{i1}$
  - $\longrightarrow$ obtain fully implicit differencing scheme
  - $\longrightarrow$ iterate equations to obtain a solution
- Advantage: large time steps ($\sim$ 5 – 15 min)
- Disadvantage: complexity, stability

PARALLEL TRANSPORT

SAMI2/3 Method: Include Ion Inertia

$$\frac{\partial n_i}{\partial t} + b_s^2 \frac{\partial}{\partial s} \frac{n_i V_{is}}{b_s} = P_i - L_i n_i$$

$$\frac{\partial V_{is}}{\partial t} + (\mathbf{V}_i \cdot \nabla) V_{is} = -\frac{1}{n_i m_i} b_s \frac{\partial (P_i + P_e)}{\partial s} + g_s - \nu_{in}(V_{is} - V_{ns}) - \sum_j \nu_{ij}(V_{is} - V_{js})$$

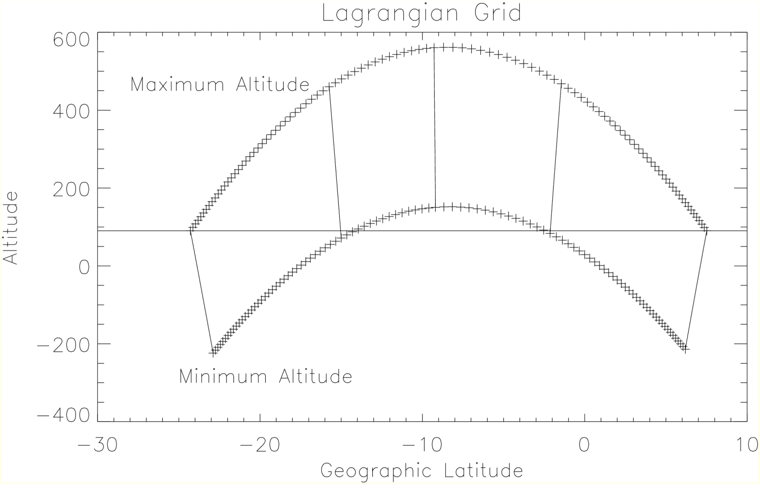
- Procedure:
  $\longrightarrow$ diffusion terms backward biased (implicit)
  $\longrightarrow$ advection terms use donor cell method
  $\longrightarrow$ obtain semi-implicit differencing scheme
- Disadvantage: small time steps ($\sim$ 5 – 15 sec)
- Advantage: simplicity, stability, flexibility, better description at high altitudes

PERPENDICULAR TRANSPORT

- Perpendicular dynamics ($E \times B$ transport)
  - Lagrangian grid: follow flux tube motion
  - Eulerian grid: fixed mesh

LAGRANGIAN GRID

Follow $E \times B$ drift of a flux tube



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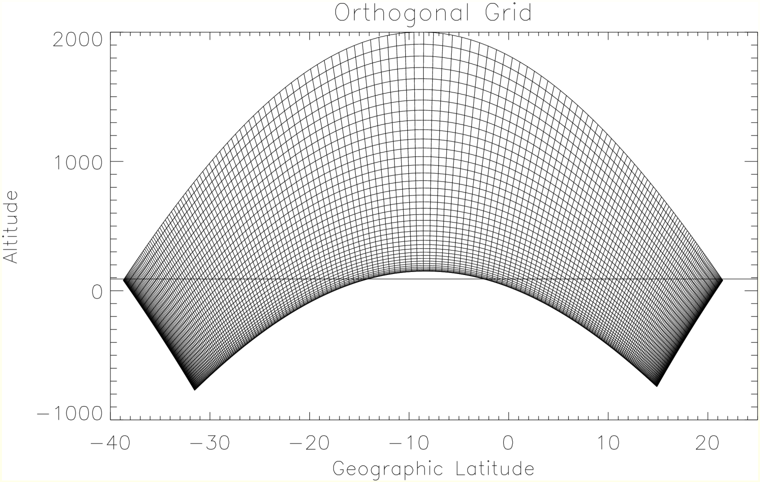
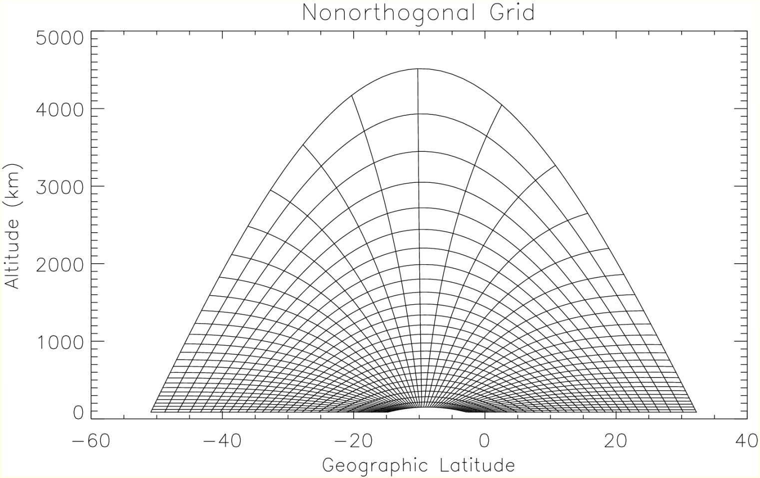
EULERIAN GRID



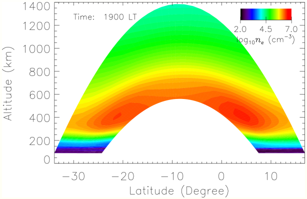
EULERIAN GRID

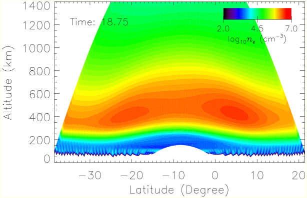
Nonorthogonal: finite volume, donor cell method

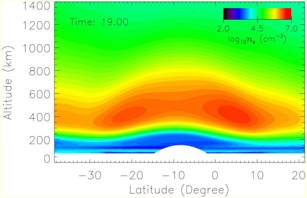


GRID COMPARISON

Lagrangian, Orthogonal Eulerian, Nonorthogonal Eulerian







OVERVIEW OF SAMI2/3

- Magnetic field: Offset, tilted dipole model / IGRF-like
- Interhemispheric / Global
- Nonorthogonal, nonuniform fixed grid
- Seven (7) ion species (all ions are equal):
  H^+, He^+, N^+, O^+, N_2^+, NO^+, and O_2^+
  - Solve continuity and momentum for all 7 species
  - Solve temperature for H^+, He^+, O^+, and e^-
- Plasma motion
  - $\mathbf{E} \times \mathbf{B}$ drift perpendicular to $\mathbf{B}$
    (both vertical and longitudinal in SAMI3)
  - Ion inertia included parallel to **B**
- Neutral species: NRLMSISE00 and HWM93
- Chemistry: 21 reactions + recombination
- Photoionization: Daytime and nighttime

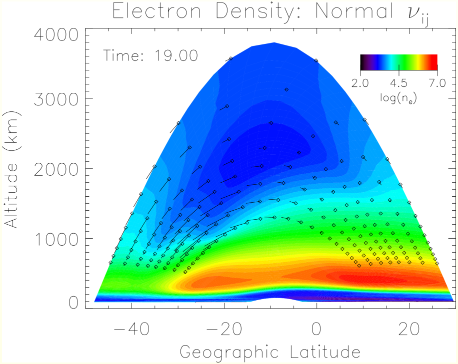
ASSORTED RESULTS

- Topside electron hole formation
- Global response to the Bastille Day flare
- Impact of penetration electric fields on the ionosphere

TOPSIDE ELECTRON HOLE FORMATION

Huba et al., *Geophys. Res. Lett.* *27*, 181, 2000

- Discovered the possible formation of a topside electron hole ($\gtrsim$ 1000 km)
- Caused by collisional coupling of transhemispheric O^+ flows with ambient H^+ ions



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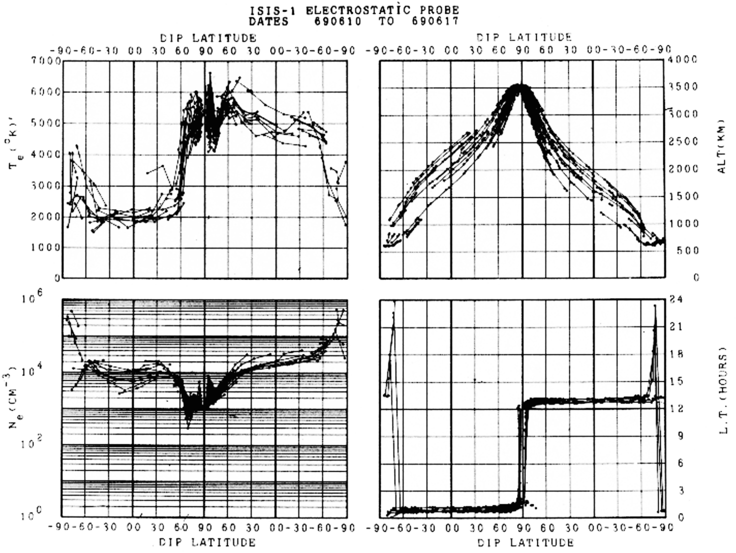
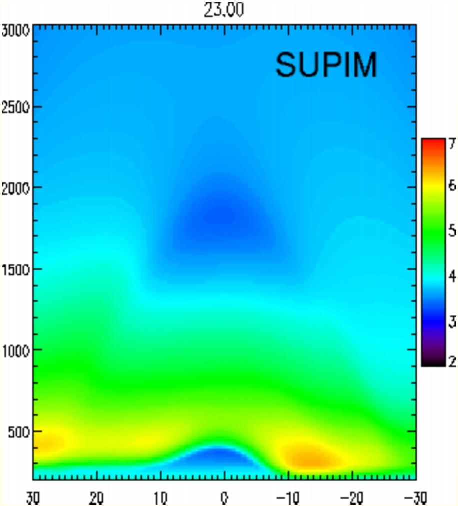
TOPSIDE ELECTRON HOLE FORMATION

ISIS data consistent with model prediction



TOPSIDE ELECTRON HOLE FORMATION

Also occurs in SUPIM (G. Bailey/B. MacPherson)

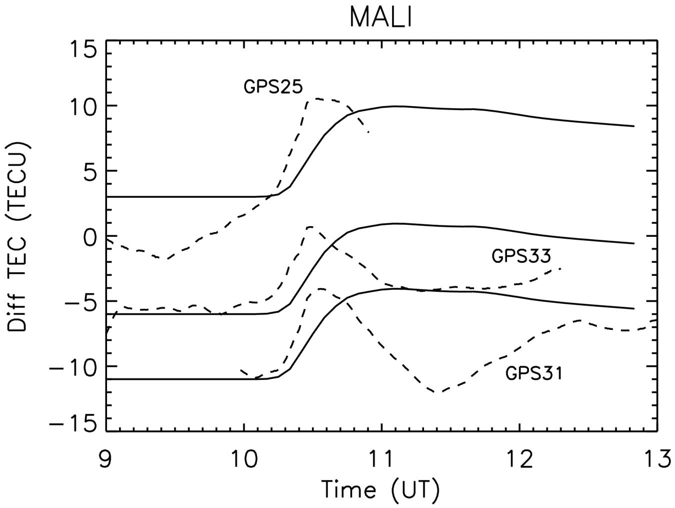


BASTILLE DAY FLARE

Huba et al., *Geophys. Res. Lett. 32*, L03S09, 2005

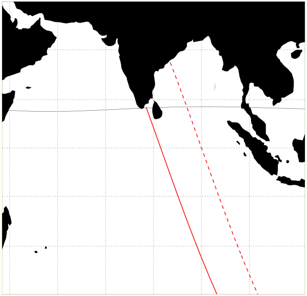
- Example - courtesy of Tom Immel
- Developed a time-dependent EUV spectrum based on data and modeling ($\Delta t = 5$ min)
- Incorporate the time-dependent EUV spectrum in the NRL ionosphere code SAMI3
- Two simulations are performed: no flare and flare
- Compare differences in electron density as well as vertical TEC, NmF2, and HmF2
- SAMI3 animation

COMPARISON TO GPS DATA

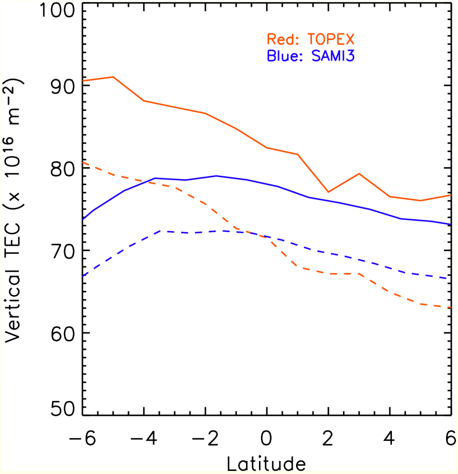


COMPARISON TO TOPEX DATA

Vertical TEC [Solid: flare day; Dashed: previous day]



TOPEX orbital paths



STORM-TIME IONOSPHERIC EFFECTS

Targeted area in NASA Living with a Star program

- The low- and mid-latitude ionosphere can become severely disturbed during large geomagnetic storms
  - Large bite-outs of electron density in the equatorial region after sunset (e.g., enhanced fountain effect) [*Basu et al.*, 2001]
  - Large increase in TEC in the afternoon, American sector (i.e., over the US) [*Foster et al.*, 2005]
- Attributed to penetration electric fields caused by breakdown of shielding of Region-2 current system
- Requires self-consistent inner magnetosphere/ionosphere model

COUPLED SAMI3/RCM MODEL

- The fundamental coupling of RCM and SAMI3 is through the solution of the potential equation

$$\nabla \cdot \underbrace{\Sigma}_{SAMI3} \cdot \nabla \underbrace{\Phi}_{RCM} = J_{\|}$$

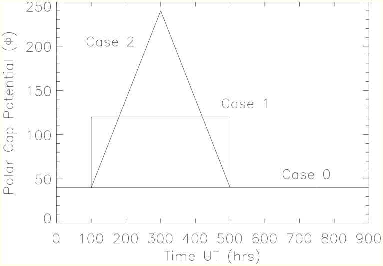
$\rightarrow$ SAMI3 provides the ionospheric conductance to RCM
$\rightarrow$ RCM solves the potential equation to determine Φ
$\rightarrow$ RCM provides the Φ to SAMI3
$\rightarrow$ SAMI3 and RCM use Φ to calculate the electric field
$\rightarrow$ Transport the plasma

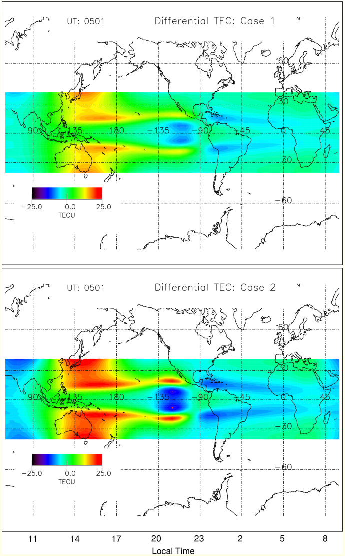
- The coupled model provides a self-consistent electrodynamicdescription of the ionosphere/inner magnetosphere system

COUPLED SAMI3/RCM MODEL RESULTS

Huba et al., submitted to *Geophys. Res. Lett.*, 2005

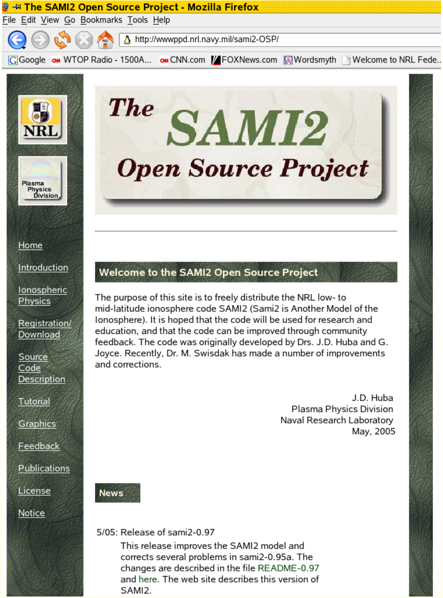
- Model storm using a time dependent polar cap potential
- Results qualitatively consistent with observations





SAMI2 OPEN SOURCE PROJECT

http://wwwppd.nrl.navy.mil/sami2-OSP/index.html



FUTURE PROJECTS

- Couple to outer magnetosphere (e.g., LFM)
  Couple to inner magnetosphere (e.g., RCM)
  Couple to thermosphere (e.g., NCAR model)
  Data assimilation (?)
- Predicated on single, fully global ionosphere model: SAMI3T (i.e., not segregated into low vs high latitude models)